

## Diagnostic criteria for computer-aided electrocardiographic 15-lead system

### *Evaluation using 12 leads and Frank orthogonal leads with vector display*

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*The criteria for the diagnosis of myocardial infarction and ischaemic heart disease by an automated 15-lead computer-aided electrocardiographic system were examined using electrocardiograms of 543 patients. Errors in the electrocardiographic diagnosis were evaluated for each lead system (Frank orthogonal 3-lead, 12-lead, and hybrid 15-lead) using clinical and catheterization data for definitive diagnosis before review of the electrocardiograms and their reports. The effects of combinations of these diagnoses and additional ventricular conduction defects were also studied.*

*Myocardial infarction and left ventricular hypertrophy were more reliably diagnosed using 3-lead and 12-lead systems together than with either system alone. The most sensitive criteria for anterior infarction were a Q/R ratio in Z < 0.1 and loss of the first 20 ms of anterior forces in the horizontal and sagittal planes of the vectorcardiogram. However, false positive results were frequent, particularly in association with left ventricular hypertrophy, non-specific intraventricular conduction defects, and left bundle-branch system block. Our V lead criteria were more specific whether or not these associated conditions were present. No single criterion with an acceptable false positive rate could be found to be sensitive for inferior infarction in all situations. Our most sensitive criteria were those based on the limb leads, and the presence of superior forces for the first 30 ms in the frontal plane of the vectorcardiogram, but these were better in combination. Limb lead criteria were the most specific. False positive results for inferior infarction were more frequent in the presence of left ventricular hypertrophy or ventricular conduction defects other than left anterior hemiblock.*

*ST and T wave abnormalities were more apparent in the 12 leads than in the orthogonal leads. Specificity and sensitivity of criteria were poor, and specificity was decreased and sensitivity was not significantly improved by combining 3-lead with 12-lead criteria. Because of frequent measurement errors of ST, T, and also Q waves by the computer programme, in practice we have achieved increased sensitivity in the diagnosis of ischaemia and infarction with the combination of 3-lead and 12-lead systems.*

*It is concluded that errors of diagnosis by a computer-aided system can be reduced by using multiple leads and that both 12-lead and orthogonal 3-lead systems are necessary for optimal computer diagnosis of left ventricular hypertrophy, myocardial infarction, and ischaemia.*

There is still controversy over the relative merits of 3-lead and 12-lead systems for computer electrocardiographic diagnosis (Caceres and Hochberg, 1970; Smith and Hyde, 1969; Bonner *et al.*, 1972; Cornfield *et al.*, 1973; Pordy *et al.*, 1968). The orthogonal 3-lead system is the simplest to use for

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such analysis, but the 12 praecordial and limb leads are more familiar to physicians. Comparisons of waveform measurements have suggested that the orthogonal system provides nearly all the information obtained from the 12-lead system in normal people (MacFarlane, Lorimer, and Lawrie, 1971; Pipberger *et al.*, 1961; Borun, Chapman, and

Massey, 1966). Though some authors have found that the diagnostic accuracy of abnormalities of waveform is similar using the two systems (MacFarlane *et al.*, 1971; Pipberger *et al.*, 1961) others disagree (Bonner *et al.*, 1972; Borun *et al.*, 1966; Talbot *et al.*, 1973), and in most studies 3-lead and 12-lead systems have been compared only in relation to specific diagnoses (Eddleman and Pipberger, 1971).

Talbot *et al.* (1973) reported their experience using both 3-lead and 12-lead systems. They found that a 15-lead electrocardiographic system and logic derived from all these leads gave the best results for myocardial infarction and right bundle-branch system block, and increased sensitivity for most diagnoses. In view of observer variation in electrocardiographic reporting (Davies, 1958), an objective method to confirm computer diagnoses is preferable (Yano and Pipberger, 1964). Using objective confirmation, Eddleman and Pipberger (1971) concluded that the Frank orthogonal 3-lead electrocardiogram was more sensitive and as accurate as the 12-lead electrocardiogram using Minnesota code classification (Blackburn *et al.*, 1960) for the diagnosis of myocardial infarction. This code was designed for epidemiological studies and similar results may not be found with more sensitive 12-lead criteria.

We have, therefore, made a further comparison of orthogonal 3-lead, vectorcardiographic, and 12-lead criteria, used in our 15-lead computer programme (Talbot *et al.*, 1973). Necropsy and catheterization data provide the most accurate confirmation of electrocardiographic diagnoses. However, restriction of any study to diseases diagnosed by such methods will select those patients with more severe disease. We have used clinical information, supported by catheter data and a few necropsies, from men and women aged 40 to 80 years.

Multiple electrocardiographic abnormalities are frequent in clinical practice, and combinations of several abnormalities may have significance different from that of single ones. In this paper we have presented our results for patients with one or more myocardial infarcts, or myocardial ischaemia, alone or in combination. We have also examined the validity of these electrocardiographic criteria of infarction and ischaemia in the presence of left ventricular hypertrophy and ventricular conduction defects.

### Subjects and methods

Electrocardiograms were obtained using an on-line automated electrocardiographic system, which has been previously described (Scheinok *et al.*, 1972;

Talbot *et al.*, 1973). Leads I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, and V6, and Frank XYZ leads were recorded simultaneously in groups of three leads. The three vector loops and the initial forces were obtained by digital-to-analogue conversion, displayed on an oscilloscope screen, and photographed with a high resolution camera. Electrocardiographic criteria were based on the 12 leads, the Frank XYZ leads, and the Frank vectorcardiogram, and hybrid criteria were formulated by combination of criteria from the three systems. However, not all statements were finally issued as an electrocardiographic report for clinical use. Some were suppressed by the computer but were preserved on a computer print-out. This enabled many different criteria and combinations of criteria to be assessed. Eighty-five per cent of all electrocardiograms recorded at Hahnemann Hospital are processed by computer.

Initially the scalar and vector electrocardiograms were examined to see whether the criteria in the programme for the diagnosis of myocardial infarction, left ventricular hypertrophy, or ischaemia, had been met. Frank 3-lead and 12-lead criteria were those in common use (Sokolow and Lyon, 1949; Allenstein and Mori, 1960; Sotobata, Richman, and Simonson, 1970; Chou and Helm, 1967; McConahay *et al.*, 1970; Gunnar *et al.*, 1967) and are presented in Table 1 which also includes vectorcardiographic criteria used in the hybrid programme.

We have already described our results in the diagnosis of conduction defects (Talbot *et al.*, 1973). In this study the following definitions have been used.

- 1) *Left bundle-branch system block*: QRS duration  $\geq 115$  ms and intrinsicoid deflection in lead X  $\geq 60$  ms; terminal R waves without Q waves in leads I or aVL.
- 2) *Complete right bundle-branch system block*: QRS duration  $\geq 115$  ms; terminal R' wave in lead V1, and R'  $\geq R + 0.2$  mV.  
Measurement of QRS duration was made in orthogonal leads, with limits based on the 95th centile of our normal population (Talbot *et al.*, 1974). In fact, complete bundle-branch system blocks almost invariably showed a QRS duration  $\geq 99$ th centile, i.e. 125 ms.
- 3) *Left anterior hemiblock*: QRS axis between  $-45^\circ$  and  $-90^\circ$  if there were a Q wave in aVL (Rosenbaum, 1969). Usually this diagnosis was associated with a QRS duration  $> 90$  ms (i.e. the lower limit of the 95th centile plus 20 ms). The diagnosis of left anterior hemiblock was not made if the R voltage in all limb leads was less than 0.5 mV.

TABLE 1

Diagnosis	12-lead criteria (A)	Orthogonal/lead criteria (B)	Vectorcardiographic criteria (C)	References
Anterior infarction	R waves $<0.1$ mV or QR with Q $\geq 0.3$ mV in 2 leads of V2-V4	Q/R ratio in Z $<0.1$	Loss of first 20 ms anterior forces in XZ and YZ planes	(B) Eddleman and Pipberger (1971) (C) Chou and Helm (1967)
Inferior infarction	Q waves $\geq 0.2$ mV and 30 ms in 2 leads of II, III, and aVF	Q/R ratio in Y $\geq 0.25$	Superior forces for first 30 ms ( $-20$ to $-180^\circ$ in XY plane)	(B) Eddleman and Pipberger (1971) (C) Chou and Helm (1967)
Lateral infarction	QR waves in V5 and V6 (Q $\geq 0.3$ mV) or R $\leq 0.1$ mV in these leads	Q/R ratio in X $\geq 0.20$		(B) Modified from Eddleman and Pipberger (1971)
Left ventricular hypertrophy	R V5 or V6 + SV1 $\geq 3.7$ mV or R $\geq 2.7$ mV in V5 or V6 or R $\geq 1.6$ mV in aVL	Voltage of R or S wave $>2.2$ mV in X, Y or Z	Maximum spatial QRS voltage $>2.0$ mV	(A) Sokolow and Lyon (1949) (B) and (C) Chou and Helm (1967); Yano and Pipberger (1964)
Anterior ischaemia	T inversion in V1 to V3, or V3 and V4 (T equal to or more negative than $-0.1$ mV)	T inversion in X (T equal to or more negative than $-0.1$ mV) or T upright and equal to or more than $0.2$ mV in Z		
Anterolateral ischaemia	T inversion in V5 and V6 (T equal to or more negative than $-0.1$ mV) or T wave inversion of more than $0.2$ mV in either V5 or V6	T inversion equal to or more than $0.2$ mV in X		
Inferior ischaemia	T inversion of more than $0.1$ mV in 2 leads of II, III, or aVF	T inversion equal to or more than $0.2$ mV in Y		
ST displacement (+ or -ve)	Difference of $\geq 0.15$ mV in ST compared with baseline	Difference of $\geq 0.15$ mV in ST compared with baseline		

4) *Intraventricular conduction delay*: QRS duration  $\geq 115$  ms, with no other criteria for bundle-branch system block.

Combined (hybrid) criteria for inferior and anterior infarction are described in Appendix A. If criteria from the 3 orthogonal leads or the vectorcardiogram or the 12 leads were fulfilled, this was described as 'or-logic'; and if criteria from either the 3 orthogonal leads or the vectorcardiogram, together with criteria from the 12 leads, were fulfilled, this was described as 'and-logic' (Talbot *et al.*, 1973). Therefore, 'and-logic' required criteria from two or more of the three systems to be fulfilled. Diagnoses were assigned qualitative probability but for this study the definite, 'probable', and 'possible' reports have been amalgamated.

All electrocardiograms recorded during a seven-week period were selected for inclusion in this study, if reported by the computer (using either 3-lead, 12-lead, or hybrid criteria) to show inferior or anterior infarction, left ventricular hypertrophy,

left or right bundle-branch system block, left anterior hemiblock, a non-specific intraventricular conduction defect, or any combination of these. Some electrocardiograms selected had been included in a previous study (Talbot *et al.*, 1973). Electrocardiograms were examined only after a complete medical record had been obtained and the clinical diagnosis determined by criteria outlined in Appendix B. In this study 961 electrocardiograms (165 men and 94 women) were examined. The diagnosis was confirmed at necropsy in 4 patients, coronary arteriography in 25, and cardiac catheterization and operation in 19. Such a study cannot include all electrocardiograms with false negative diagnoses.

To avoid this bias in favour of computer criteria, we examined the final diagnosis for each patient in hospital during this period; if the diagnosis were myocardial infarction or if a cause for left ventricular hypertrophy could be established (see Appendix B) the electrocardiograms were examined. This group

comprised 908 electrocardiograms from 112 men and 70 women. For analysis of myocardial ischaemia, we examined an additional 289 electrocardiograms from 102 patients coded as ischaemic heart disease (400-404 and 410, International Classification of Diseases, 8th Revision, 1967-1969) and confirmed by coronary angiography.

Each electrocardiogram was examined for diagnostic features of myocardial infarction, left ventricular hypertrophy, and ischaemia (Table 1). These features included all the criteria, including the hybrid criteria described. From this analysis computer measurement errors were identified and all other errors of diagnosis in relation to the clinical diagnosis were described as criteria errors. In all, 1869 electrocardiograms of 441 patients were examined for accuracy of diagnostic statements of myocardial infarction and left ventricular hypertrophy and 2158 electrocardiograms (543 patients) were examined for ST and T wave abnormalities. The latter were divided into ST segment depression and ST segment elevation, specific T wave abnormalities of ischaemia as detailed in Table 1, and

non-specific T wave abnormalities, consisting of all T wave abnormalities in any one of the 12 leads, and T waves of 0.1 mV or less in multiple leads, or X, Y, or Z, which could not be described as diagnostic of ischaemia.

The majority of errors of diagnosis were criteria errors. Separate analysis of the results from the three groups of electrocardiograms did not lead to any different conclusions, and the results have therefore been amalgamated. Only the 12-lead, orthogonal 3-lead, and vectorcardiographic criteria that were found most satisfactory have been presented.

In this study we have clearly distinguished between false positive criteria and false positive measurement errors, but have not detailed false negative results because of our inability to localize the areas of ischaemia or infarction by coronary arteriography.

## Results

The results of anterior and inferior infarction criteria are shown in Table 2. Myocardial infarction

TABLE 2 Comparison of diagnostic criteria\* for myocardial infarction

Clinical group	Electrocardiographic lead system	Anterior infarction criteria positive			Inferior infarction criteria positive			No ECG criteria of infarction	Total ECGs on patients with infarction
		Clinical criteria for infarction present	No clinical infarction	False positive (%)	Clinical criteria for infarction present	No clinical infarction	False positive (%)		
I Myocardial infarction only	a) 12-lead	101	18	(15.1)	135	22	(14)	153	343
	b) XYZ leads	181	38	(17.4)	89	8	(8.3)	136	343
	c) Vector	167	24	(12.6)	134	29	(17.7)	108	343
	d) Hybrid 15-lead	190	45	(19.1)	136	14	(9.3)	97	343
II Myocardial infarction and left ventricular hypertrophy	a) 12-lead	105	28	(21.1)	127	27	(17.5)	65	280
	b) XYZ leads	162	84	(34.1)	79	20	(20.2)	81	280
	c) Vector	159	81	(33.8)	137	64	(37.4)	42	280
	d) Hybrid 15-lead	184	99	(35.0)	128	29	(18.5)	31	280
III Myocardial infarction and intraventricular conduction defect	a) 12-lead	18	7	(28.0)	44	10	(18.5)	39	97
	b) XYZ leads	12	13	(52.0)	29	2	(6.4)	65	97
	c) Vector	11	11	(50.0)	42	9	(17.6)	53	97
	d) Hybrid 15-lead	16	22	(57.9)	47	10	(17.5)	45	97
IV Myocardial infarction and RBBB	a) 12-lead	31	9	(22.5)	58	24	(29.3)	30	105
	b) XYZ leads†	—	—	—	42	8	(16.0)	—	105
	c) Vector	36	13	(26.5)	48	17	(26.1)	33	105
	d) Hybrid 15-lead	42	13	(23.6)	57	25	(30.4)	21	105
V Myocardial infarction and LAHB	a) 12-lead	44	4	(8.3)	46	2	(4.1)	22	108
	b) XYZ leads	68	5	(6.8)	45	0	(0)	14	108
	c) Vector	66	5	(7.0)	45	0	(0)	22	108
	d) Hybrid 15-lead	81	7	(8.0)	51	2	(3.8)	6	108

\*Excluding measurement errors.

Percentages of false positive diagnoses were calculated in relation to electrocardiographic diagnoses and are shown in parentheses. Details of criteria are in Table 1 and Appendix A.

†Orthogonal criteria for anterior infarction and right bundle-branch block are not presented because of the low R wave voltage of Z and therefore inaccurate values of Q/R ratio in Z.

Abbreviations: RBBB=right bundle-branch block; LAHB=left anterior hemiblock.

is often present even when electrocardiographic features are not. We have, therefore, concluded that the criterion most often found in association with clinical evidence of infarction was the most sensitive sign of infarction in this area. Criteria were often fulfilled for different localizations of infarction in the same patient using different systems; for this reason separate analysis of anterior

and inferior criteria together, anterior criteria alone, and inferior criteria alone would be misleading.

### Anterior myocardial infarction

The most sensitive criterion for anterior infarction was a Q/R ratio in Z < 0.1, but loss of anterior forces in the sagittal and horizontal planes of the vectorcardiogram was almost as sensitive. Computer hybrid criteria were even more sensitive, because of occasional discrepancies between these two diagnostic criteria. In some infarctions (Fig. 1A) there was early posterior orientation of initial forces for 20 ms (XZ plane), which then turned sharply forward so that the Q/R ratio in Z was preserved, whereas in others the first 10 ms forces were anterior though the next 20 ms forces were posterior (Fig. 1B). Early posterior orientation of horizontal forces was often associated with a narrow R wave in V1 to V3. Occasionally the only positive indication of old anterior infarction was a Q wave of 0.1 mV and less than 20 ms duration in two of the three leads V2, V3, and V4, but an isolated small Q wave in the transition zone was not significant. Associated left ventricular hypertrophy produced more false-positive results, particularly with orthogonal and vectorcardiographic criteria, but there were few electrocardiograms of patients with infarction in which the diagnosis was not suggested by 15 leads (Fig. 2).

Left bundle-branch system block was found in only 20 electrocardiograms of patients with infarction; though a hybrid 15-lead diagnosis of anterior infarction was correctly made in 17 electrocardiograms, there were 48 (73.8%) false-positive results, mainly because of vectorcardiographic and orthogonal criteria. Q waves rarely spread to V4 in the absence of infarction. Right bundle-branch system block was not associated with significantly more false-positive results, but Q waves in V1 to V3 were sometimes falsely detected, probably because of the low voltage of the initial R wave. The R wave in lead Z is often of low voltage in right bundle-branch system block, so that in our experience the Q/R ratio in Z is not satisfactory in this condition. However, the absence of a Q in Z is an indication of anterior myocardial infarction. Right bundle-branch system block was particularly associated with QR complexes in V1 to V4, but QR complexes were of more significance than QS waves in all conditions except in V4. Left anterior hemiblock did not appear to affect the diagnosis of anterior infarction. Non-specific intraventricular conduction defects reduced the specificity of all criteria for anterior infarction and sensitivity may also have been reduced.

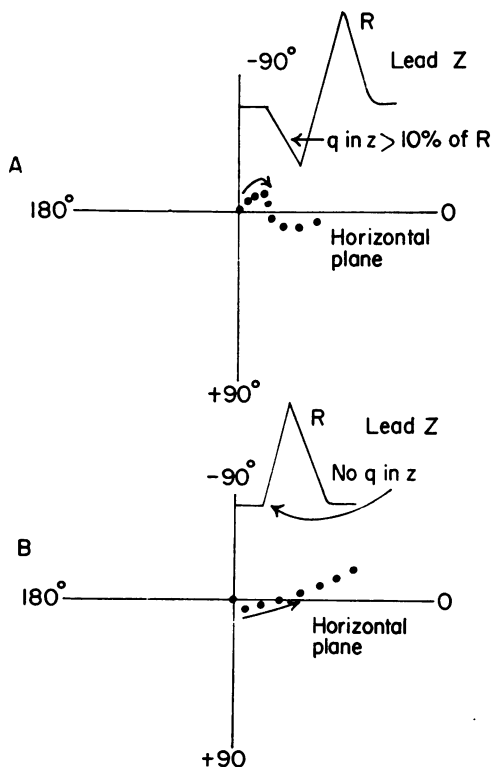


FIG. 1 Diagrammatic representation of the initial 40 ms forces of the horizontal plane of the vectorcardiogram and lead Z of the Frank electrocardiogram. (A) The initial 20 ms forces of the vectorcardiogram are directed posteriorly and yet Q/R ratio is normal. No initial R wave was detected by the computer or the cardiologist though a small R wave must have been present simultaneously with the initial 20 ms forces of the vectorcardiogram. (B) The initial 10 ms forces of the vectorcardiogram are slightly anterior but the later forces are posterior. No Q wave in lead Z was detected by the computer or the cardiologist though a small Q wave must have been present simultaneously with the initial 10 ms forces of the vectorcardiogram.

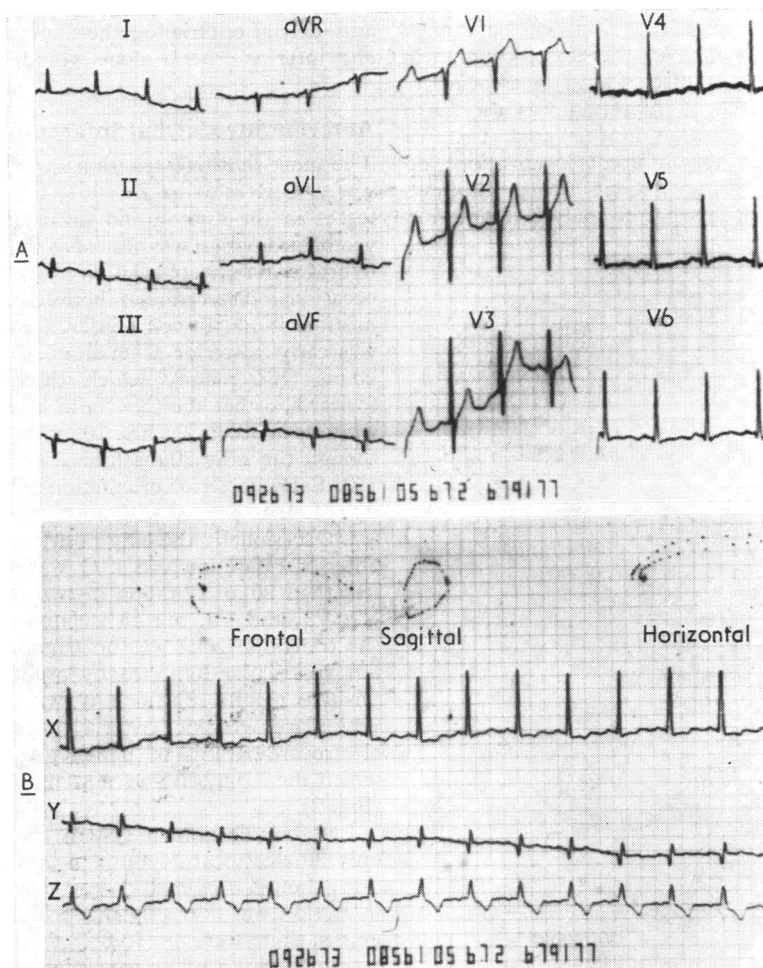


FIG. 2 Electrocardiograms and vectorcardiographic loops of a 52-year-old man. Serial records had shown the development of inferior and true posterior infarction, with a prominent R wave in V1 and V2. There was clinical evidence of myocardial infarction initially and further infarction developed six months later. (A) The 12-lead electrocardiogram at this time is shown. This did not show any significant change from the earlier record. (B) Vectorcardiogram and orthogonal leads X, Y, and Z. Above, from left to right: frontal, sagittal, and horizontal plane vector loops. Below, orthogonal leads X, Y, and Z. Both the Q wave in Z and anterior forces were lost, compared with the electrocardiogram taken six months earlier. The rightward orientation of the initial forces probably indicates lateral infarction as well. These changes persisted, and show the value of Frank 3 leads for the sensitive diagnosis of anterior myocardial infarction.

### Inferior myocardial infarction

The most sensitive of the selected single-lead criteria for inferior infarction was the presence of a Q wave in lead aVF of  $\geq 0.2$  mV. In fact Q waves of 0.1 mV were even more sensitive and Q waves of 0.1 mV in leads II, III, and aVF were usually associated with clinical infarction. Loss of inferior

forces was also a sensitive criterion but, as with Q in lead III alone, produced an unacceptable number of false-positive results, particularly in the presence of left ventricular hypertrophy. False negative results occurred in typical inferior infarction when there was associated lateral infarction in which initial forces in the frontal plane were sometimes diverted to the right and slightly inferiorly,

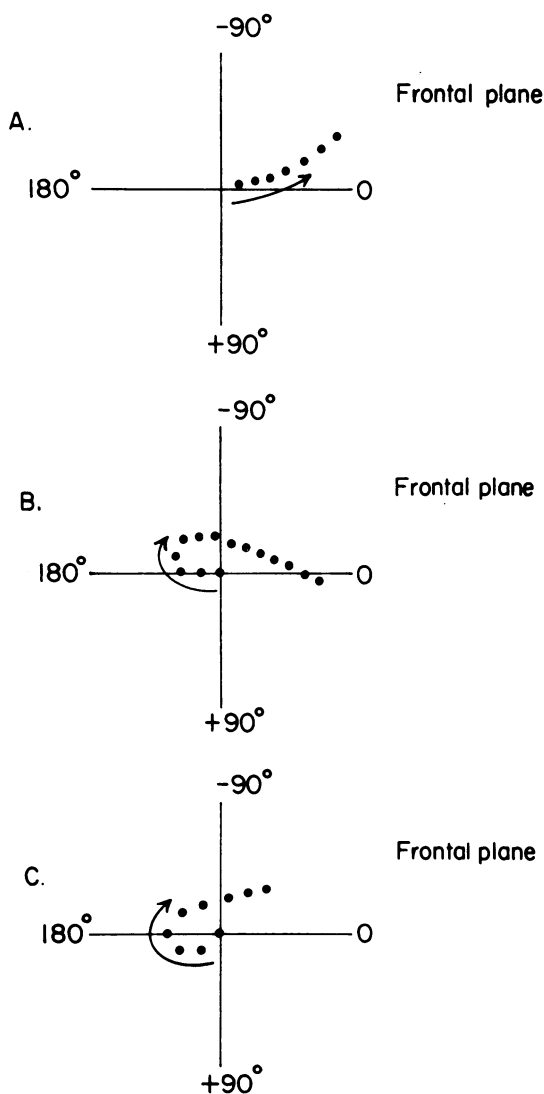


FIG. 3 Frontal plane vectors in inferior infarction (5 ms interval markers). (A) The initial forces are directed superiorly and to the left at  $-20^\circ$  with counterclockwise rotation. However, there is distinct left axis deviation. (B) The initial 10 ms forces are horizontal but the rotation of the loop is clockwise and the axis is horizontal. (C) The initial 10 ms forces are directed inferiorly and to the right before turning clockwise and to the left. The axis is usually horizontal. The first configuration may or may not be associated with inferior infarction; the latter two usually are associated with inferior infarction.

but Q waves were present in leads II and aVF (or Y) (Fig. 3).

Left ventricular hypertrophy was associated with superior forces for the initial 30 ms when the frontal plan QRS axis was vertical ( $\geq +45^\circ$ ) in the absence of infarction; this increased the number of false-positive results for inferior infarction in all lead systems. In the presence of left bundle-branch system block and left anterior hemiblock (or left axis deviation), R waves were often small in the absence of infarction and Q waves occasionally appeared in III and aVF but not in II. False-positive results were common in the presence of combined right bundle-branch system block and left anterior hemiblock, probably because a very small initial R wave was not detected; this was followed by a conspicuous S wave before the terminal R' wave in III and aVF. The vectorcardiogram was often necessary to confirm initial inferior forces. Non-specific intraventricular conduction defects were commonly found in association with criteria of inferior infarction and slightly increased false-positive results.

#### Optimal computer criteria for infarction

Hybrid computer criteria were the most sensitive for anterior and inferior infarction, and the presence of specific criteria resulting in a diagnosis of probable or definite infarction correlated well with the clinical diagnosis. The most specific criteria for inferior and anterior infarction have been tested (Table 3) so that diagnoses can be assigned a degree of probability. Loss of specificity for anterior infarction resulted from inclusion of the Q wave in V3 without Q in V4, particularly in association with left ventricular hypertrophy and intraventricular conduction defects, and there was loss of specificity for inferior infarction with reduction of Q/R ratios. We noted that Q/R ratios were valid even with Q waves of 0.1 mV, when a W-shaped complex was often seen. The Q wave in III added little that could not be obtained from aVF alone, and a Q wave  $\geq 0.2$  mV in lead aVF was only slightly more specific and less sensitive than the 12-lead combined criteria of the computer programme. However, the additional presence of a Q wave of  $\geq 0.2$  mV in II, particularly if the Q/R ratio  $\geq 25$  per cent, considerably enhanced the specificity of a Q wave in III or aVF. Even a Q wave of 0.1 mV in II was supportive evidence for other criteria of inferior infarction. A Q/R ratio in II, III, and aVF of over 0.25 was almost diagnostic of inferior infarction, and was associated with a rightward and superior direction of the initial 30 ms forces in the frontal plane.

TABLE 3 *Specific diagnostic criteria\**

	<i>Positive criteria for inferior infarction**</i>				<i>Positive criteria for anterior infarction**</i>				
	<i>Q/R in II+III+ aVF</i>	<i>Q/R in II+ aVF</i>	<i>Q Waves in II+III+ aVF</i>	<i>Q Waves in II+ aVF</i>	<i>Q Waves in V2-V4</i>	<i>Q Waves in V3+V4</i>	<i>Q Waves in V4</i>	<i>Q Waves in V2+V3</i>	<i>Q Waves in V3</i>
	$\geq 0.25$	$\geq 0.25$	$\geq 0.2$ mv	$\geq 0.2$ mv					
Clinical criteria for infarction present	181	186	299	314	146	213	223	277	315
False positive†	15 (7.7)	17 (8.4)	30 (9.1)	39 (11.0)	12 (7.6)	20 (8.6)	22 (9.0)	63 (18.5)	68 (17.8)

\*Excluding patients with left bundle-branch block. Total number of electrocardiograms examined=933.

\*\*Less specific criteria are not shown. Specificity increases from right to left for both inferior and anterior infarction criteria.

†Percentage of false positives in parentheses.

### Lateral infarction

Criteria for lateral infarction were only fulfilled in 15.2 per cent of cases with myocardial infarction. Though the presence of Q waves in leads V5 and V6 together did decrease sensitivity, this combination was still superior to the Q/R ratio  $\geq 0.20$  in X. No example of high lateral infarction with changes confined to leads I and aVL or high praecordial leads was noted during this study. During the period of the study, 11 electrocardiograms (2

patients) were found in which criteria for lateral infarction only were satisfied; in these electrocardiograms the V-lead criteria were superior to Q/R ratio in lead X.

### Myocardial ischaemia

ST and T wave criteria errors in 3-lead and 12-lead electrocardiograms are shown in Table 4. A separate analysis of T wave abnormalities for each

TABLE 4 *Diagnostic accuracy of ST and T wave criteria for ischaemia*

<i>Electrocardiographic diagnosis</i>	<i>Clinical diagnosis</i>	<i>No other abnormality</i>		<i>Left ventricular hypertrophy</i>	
		<i>XYZ</i>	<i>12-lead</i>	<i>XYZ</i>	<i>12-lead</i>
<i>*Anterolateral ischaemia</i>					
T inversion V5 and V6	Clinical and electro-cardiographic positive	184	209	84	99
	False positive criteria†	9 (4·7)	10 (4·6)	259 (75·5)	269 (73·1)
<i>*Anterior ischaemia</i>					
T inversion in X	Clinical and electro-cardiographic positive	12	24	8	19
T inversion in any 2 leads of V2 to V4	False positive criteria†	0 (0)	0 (0)	0 (0)	0 (0)
T upright in Z, T inversion in X					
<i>*Inferior ischaemia</i>					
T inversion in any 2 leads of II, III, aVF	Clinical and electro-cardiographic positive	70	92	30	42
T inversion in Y	False positive criteria†	0 (0)	0 (0)	41 (57·7)	44 (51·2)
<i>Inferior ST depression</i>					
ST depression in any 2 leads of II, III, aVF	Clinical and electro-cardiographic positive	7	13	8	16
ST depression in Y	False positive criteria†	0 (0)	0 (0)	11 (57·9)	22 (57·9)
<i>Anterior ST depression</i>					
ST depression in any 2 leads of V2 to V6	Clinical and electro-cardiographic positive	71	86	67	76
ST depression in X	False positive criteria†	3 (4·1)	6 (6·5)	149 (69·0)	168 (68·9)
<i>ST elevation</i>					
ST elevation in any 2 leads of V1 to V6	Clinical and electro-cardiographic positive	47	59	6	9
ST elevation in X	False positive criteria†	1 (2·1)	0 (0)	2 (25)	2 (18·4)
<i>Non-specific T wave changes</i>					
Normal T waves		234	240	179	152
		119	79	25	18
<i>Total number of electrocardiograms with ischaemia</i>		589		316	

\*Some patients showed both inferior and anterior ST and T wave changes, see Table 1 and text for full criteria.

†Percentages of false-positive results are in parentheses.

conduction defect was performed, and since T wave abnormalities in the presence of left bundle-branch system block did not appear to be of diagnostic value, they have been excluded from this table. ST depression and T wave changes were not specific for ischaemia even if there were normal intraventricular conduction and no evidence of left ventricular hypertrophy. Specificity of T wave inversion and ST depression in both 3-lead and 12-lead electrocardiograms was reduced in the presence of left ventricular hypertrophy, particularly if there were electrocardiographic features of left ventricular hypertrophy. Sensitivity was greater for the 12-lead than for 3-lead criteria, and this was out of proportion to the slightly greater diagnostic specificity of our 3-lead criteria for anterior ischaemia. The 3-lead criteria of this programme were particularly insensitive to anterior without lateral ischaemic changes, and better 3-lead criteria must be devised. False-positive results for anterior ischaemia occur in the presence of right bundle-branch system block, since T wave inversion, sometimes with ST depression, can extend as far as V3 in the absence of ischaemia, and this state-

ment is suppressed by the computer. ST segment depression, particularly in inferior leads, was moderately specific for ischaemia in the absence of left ventricular hypertrophy, non-specific intraventricular conduction defects, or right bundle-branch block. It was noted that T wave inversion without ST segment depression was of greater diagnostic value for ischaemia than similar T wave inversion with ST segment depression in the presence of left ventricular hypertrophy, non-specific intraventricular conduction defects, or right bundle-branch block. Inferior ST and T wave changes were more specific than those in V5 and V6, but they were less frequent. There were rarely normal T waves in the presence of ischaemic heart disease and left ventricular hypertrophy. ST elevation was specific for ischaemia in all conditions.

### Measurement errors

Errors of measurement of QRS, which resulted in false positive diagnoses of myocardial infarction occurred sometimes in the 12-lead system and sometimes in the orthogonal lead system and vectorcardiogram. An irregular baseline, as with atrial fibrillation or flutter or technical difficulties, was an important cause of error particularly affecting measurement of the Q wave. Because of discrepancies between these systems the 15-lead system led to improvement in sensitivity of diagnosis.

Measurement errors of the ST segment and T wave in a sub-sample of 786 electrocardiograms compared with the cardiologist's interpretation are shown in Table 5. Orthogonal leads were not only less sensitive to ST and T wave changes, but there were as many errors of measurement in this system as in the V leads. The computer programme failed to detect ST changes in both 12 leads and orthogonal leads and there were both false-positive and false-negative results for T wave changes. Occasionally ST elevation or depression was incorrectly reported. The principal discrepancy between orthogonal and 12-lead systems was T wave inversion in V1 to V4 (anterior ischaemia); this abnormality was often not visible in orthogonal leads. Occasionally this V-lead diagnosis was made incorrectly in the presence of a negative QRS and a pronounced upwards ST slope merging into the T wave, when the latter part of the positive T wave was considered to be inverted in these leads by the computer.

### Discussion

Most studies of orthogonal, vectorcardiographic, and 12-lead criteria have been concerned with the

<i>Left ventricular hypertrophy and any ventricular conduction defect</i>		<i>Any ventricular conduction defect alone</i>	
<i>XYZ</i>	<i>12-lead</i>	<i>XYZ</i>	<i>12-lead</i>
18	24	29	32
52 (74.3)	67 (73.6)	65 (69.1)	76 (70.9)
13	18	13	25
4 (23.5)	12 (40.0)	5 (27.8)	18 (41.8)
9	11	18	24
9 (50.0)	10 (47.6)	3 (14.3)	4 (14.3)
4	5	2	2
2 (33.3)	2 (28.6)	15 (8.8)	16 (8.9)
48	52	47	57
75 (61.0)	90 (63.4)	78 (62.4)	87 (60.4)
4	5	1	1
0 (0)	0 (0)	0 (0)	0 (0)
87	80	100	83
1	0	20	16
123		176	

TABLE 5 Accuracy of computer diagnosis of ST and T wave changes (measurement errors)\*

Electrocardiographic diagnosis	XYZ leads Total number of cardiologist's statements	Computer and cardiologist positive	False positive computer diagnosis†	False negative computer diagnosis	12 leads Total number of cardiologist's statements	Computer and cardiologist positive	False positive computer diagnosis†	False negative computer diagnosis
Anterolateral ischaemia	225	198	3 (1.5)	27	255	222	4 (1.8)	33
Inferior ischaemia	77	64	3 (4.5)	13	103	79	2 (2.5)	24
Anterior ischaemia	22	21	0 (0)	1	40	34	1 (2.9)	16
Anterior or inferior ST elevation	50	20	0 (0)	30	61	22	2 (8.3)	39
Anterior ST depression	164	129	8 (5.8)	35	213	168	11 (6.1)	35
Inferior ST depression	10	9	1 (10)	1	22	18	1 (5.3)	4
Non-specific T changes	326	235	2 (0.8)	91	315	231	2 (0.4)	84

\*The computer statement has been compared with the cardiologist's interpretation using the same criteria as produced the computer statement.

†Percentage false positive statements, in parentheses, are expressed in relation to the number of positive electrocardiographic diagnoses by computer.

diagnostic accuracy of such criteria, using various mathematical methods (Simonson, 1961), which assign equal importance to false-positive and false-negative results. However, in epidemiological and clinical work, requirements may differ, and statements of both specificity and sensitivity may be necessary.

The sensitivity of any test is measured by the percentage of people with the disease under consideration, who are correctly classified by the test. Specificity is calculated from the percentage of people without the disease, who have a negative result to the test. Sensitivity is affected by the population examined. Mildly affected patients may not be subjected to the test, and test records of more severe cases may not be obtainable for logistic or humanitarian reasons. Also, specificity (by the definition given) is greatly affected by the variety of clinical conditions in the population which are frequently confused with the diagnosis under investigation. A more useful measurement is the predictability of the test, i.e. the percentage of correct positive diagnoses by the test in relation to the total number of positive tests. The predictability of the electrocardiographic criteria and the percentage of false-positive results have been measured in this study, but this is only related to specificity in the hospital population examined and might not be applicable in other situations.

Myocardial infarction cannot be localized without pathological or electrocardiographic information, and therefore false-positive results may actually be higher than indicated. We cannot determine the frequency of false-negative electrocardiographic diagnoses without necropsy evidence. For all these reasons the proportion of false-negative diagnoses and sensitivity cannot be determined. However, if

there has been no selection of cases, the diagnostic sensitivity of different criteria in various conditions can be and has been compared. Catheterization data have been used for infarct localization (McConahay *et al.*, 1970), but with diffuse arteriographic disease, localization of infarction is only presumptive. Various clinical methods have been used to circumvent this difficulty, e.g. use of generally accepted 12-lead criteria (Eddleman and Pipberger, 1971) or the time sequence of evolutionary changes in relation to the history and investigations (Young and Williams, 1968; Goldberger, 1945). We have analysed our results by these methods, but they are open to criticism and the results did not affect our conclusions.

The electrocardiogram may be normal in the presence of infarction, and may vary from day to day; therefore no criterion can be absolutely specific or sensitive (Cawood *et al.*, 1974a, b; Willems, Poblete, and Pipberger, 1972). The results of this study suggest that diagnostic sensitivity for myocardial infarction and ventricular conduction defects is usually improved by 15-lead hybrid criteria and that the computer statement of probable or definite infarction corresponds satisfactorily with the actual diagnosis.

Superior forces for  $\geq 30$  ms and clockwise inscription of the first 25 to 30 ms in the frontal plane have been proposed as sensitive criteria for inferior infarction (McConahay *et al.*, 1970; Young and Williams, 1968; Hugenholtz, Forkner, and Levine, 1961; Murata *et al.*, 1967). It has been suggested that the vectorcardiographic appearance of inferior infarction is preserved in the presence of left anterior hemiblock (Kulbertus *et al.*, 1971). However, this study suggests that vectorcardiographic criteria are no more sensitive than 12-lead

criteria. Vector loops may vary considerably and the initial inscription is affected by the later direction of the QRS; clockwise rotation may occur without infarction if there is a vertical axis ( $\geq +45^\circ$ ) and inferior infarction may occur with counter-clockwise rotation, particularly with left axis deviation (Gunnar *et al.*, 1967), and sometimes with left anterior hemiblock. A Q/R ratio  $\geq 25$  per cent in aVF may be the best single discriminating factor between normal hospital patients and patients with inferior infarction (Simonson, 1961). Increasing duration of the Q wave increases specificity (Myers, Klein, and Hiratzka, 1949), and a Q wave duration  $>0.04$  s in aVF is the next most accurate single-lead criterion (Simonson, 1961). However, combinations of leads have not been tested adequately.

Specific vectorcardiographic appearances in the horizontal plane have been described for anterior infarction (Hugenholz *et al.*, 1963), and it has been thought that these remain specific in the presence of left ventricular hypertrophy. Our results and those of others (Kini, Eddleman, and Pipberger, 1970) conflict with this view. All criteria of anterior infarction were less specific in the presence of left ventricular hypertrophy; the vectorcardiographic and orthogonal criteria were less specific than the V lead criteria, though QS waves in V1 and V2 and sometimes also in V3 were frequent findings in uncomplicated left ventricular hypertrophy.

The diagnosis of inferior or anterior infarction cannot be made by usual criteria in the presence of left bundle-branch system block because of frequent false-positive results. Moreover, left bundle-

branch system block may conceal the changes of anterior and inferior infarction (Luy, Bahl, and Massie, 1973). The diagnosis of left anterior hemiblock did not appear to influence the diagnosis of inferior or anterior infarction. Though it has been pointed out that the changes of inferior infarction and anteroseptal infarction may be modified by left anterior hemiblock as a result of inferior direction of the initial 20 ms forces, this does not seem of great importance. In our experience, right bundle-branch system block has little effect on the diagnosis of inferior and anterior infarction, in contrast with the findings of Goldman and Pipberger (1969). Occasionally there was an increase in the initial anterior 20 ms forces in patients with infarction who developed right bundle-branch system block, even if there were V-lead electrocardiographic evidence of anterior infarction on the previous tracing. This increase of anterior forces might occasionally obscure anterior infarction or suggest true posterior infarction, and should be suspected if there is clockwise rotation of the vector loop in the horizontal plane. In conclusion, criteria which are used for the diagnosis of inferior and anterior infarction have been arranged in order of increasing sensitivity and decreasing specificity in Table 6.

Many factors influence ST and T wave changes (Varriale, Alfenito, and Kennedy, 1966), and we, therefore, do not use them for left ventricular hypertrophy diagnostic logic. This study indicated that the diagnosis of left ventricular hypertrophy was not supported by the presence of intraventricular conduction defect or delayed intrinsicoid deflection as was suggested by Estes (1966), though

TABLE 6 Diagnostic criteria for a computer system\*

Inferior infarction†	Anterior infarction†
1) Q II, III, and aVF (or Y) $\geq 0.2$ mV and $\geq 25\%$ of R wave	1) Q V2, V3, and V4
2) Q II, III, and aVF (or Y) $\geq 0.1$ mV and $\geq 25\%$ of R wave	2) Q V3 and V4
3) Q II and aVF (or Y) $\geq 0.2$ mV and $\geq 25\%$ of R wave	3) QR V2 and V3
4) Q III, and aVF (or Y) $\geq 0.2$ mV and $\geq 25\%$ of R wave and Q II $\geq 0.2$ mV	4) QR V4
5) Q II and aVF (or Y) $\geq 0.2$ mV only and Q III $\geq 0.2$ mV and $\geq 25\%$ of R wave	5) QR V3
6) Q II, III, and aVF (or Y) $\geq 0.2$ mV only	6) QR V2
7) Q II $\geq 0.2$ mV only, Q aVF (or Y) $\geq 0.2$ mV and $\geq 25\%$ of R wave	7) QS V2 and V3
8) Q II, III, and aVF (or Y) $\geq 0.2$ mV only	8) QS V3
9) Q III and aVF $\geq 0.2$ mV only	9) QS V2
10) Q aVF $\geq 0.2$ mV only	10) Q V2 or V3
11) Superior forces for $\geq 30$ ms in frontal plane of VCG	11) Q V2 or V3 or V4
	12) First 20 ms forces posterior in horizontal and sagittal planes of VCG
	13) Q in Z $< 10\%$ of R wave

\*Criteria are arranged in order of increasing specificity and decreasing sensitivity from below upwards.

†Q waves all of  $\geq 30$  ms for inferior infarction and Q waves all of  $\geq 20$  ms in V leads for anterior infarction.

in patients under 37 years of age, in whom multiple disorders are uncommon, such criteria might be of value. The gradual slope of ST depression from a normal J point to a wholly inverted T wave or an initially inverted T wave, often with a terminal upright T wave in anterolateral leads, is more typical of left ventricular hypertrophy than of ischaemia, but such appearances are difficult to quantify and may be misleading. Repolarization changes particularly in the frontal plane may be the result of left anterior hemiblock (Gomes, Lima, and Romalhao, 1975). Descriptive statements about ST segment deviation and T wave inversion were issued by the computer and were clinically useful; only if there are pronounced ST segment changes can they be used to support a diagnosis of infarction.

Description of ST and T wave changes forms an important part of an electrocardiographic report. Because of the lack of sensitivity of our orthogonal lead criteria for ST and T wave changes and measurement errors, false-negative interpretation may occur. Though it is possible that better criteria could be devised, the criteria used had been found to produce the most acceptable number of false-positive and false-negative results. Further criteria based on the orthogonal leads and vectorcardiographic T wave loops may be of value when data from such loops have been quantified satisfactorily, but so far we have had little success with simple angular criteria. A 12-lead electrocardiogram may appear to reduce criteria errors to a satisfactory level, but the use of 15 leads with hybrid 'or-logic' reduces false-negative measure-

ment errors and increases sensitivity of diagnosis; this increases false-positive results, and necessitates further hybrid 15-lead 'and-logic' so that more definite T wave statements can be made.

At present it is impossible to report quantitative levels of probability, since though the range of electrocardiographic measurements for the population is known, it is necessary to have these from cases with all the diagnoses causing false-positive and false-negative computer reports. It is often difficult to reach a final diagnosis in life, particularly if there are multiple abnormalities, but such diagnoses must be made if the reference source of confirmed diagnoses is to be as unselected as possible. For example, patients with old infarction (and these were mostly 'probable infarctions'; see Appendix B) fulfilled fewer electrocardiographic criteria for infarction; multiple infarctions may conceal individual infarction criteria. All these cases must be included in the reference source if valid estimates of numerical probability are to be given for any diagnosis. Less common conditions, such as right ventricular hypertrophy and emphysema, may complicate such logic.

In Table 7 the optimal lead systems for various diagnoses are presented, based on our current results (Talbot *et al.*, 1973). Left ventricular hypertrophy voltage criteria provide a good example of the value of multiple lead systems since no single system is sufficiently sensitive without producing excessive false-positive results. In isolation the vectorcardiographic criteria of left ventricular hypertrophy were more specific yet as sensitive as the V-lead criteria of left ventricular hyper-

TABLE 7 Requirements for computer-aided electrocardiogram system

12-lead criteria	Frank 3-lead and vectorcardiographic criteria	Hybrid 15-lead criteria
Axis, hemiblocks	Sensitive diagnosis of left ventricular hypertrophy	Specific diagnosis of anterior infarction ('and-logic')
Right bundle-branch system block (complete and incomplete)	Right ventricular hypertrophy	Specific diagnosis (and-logic) and sensitive diagnosis (or-logic) of inferior infarction
Anterior ischaemia	Sensitive diagnosis of anterior infarction	Left bundle-branch system block
Non-specific abnormalities of ST-T wave		Marginal improvements in specific ('and-logic') and sensitive ('or-logic') diagnoses of ischaemia and left ventricular hypertrophy
Specific diagnosis of anterior infarction		
Specific diagnosis of left ventricular hypertrophy		
Anterolateral ischaemia		
Inferior ischaemia		
Lateral infarction		

trophy. The most specific criteria were the limb lead criteria of Sokolow and Lyon (1949) with adjustments for the normal limits of QRS voltage that can be expected from axis changes.

We believe that a 15-lead system with hybrid logic does produce better results than either a 12-lead or a 3-lead orthogonal system used alone. A Frank orthogonal system alone does not seem satisfactory for hospital practice though a 12-lead system alone might be sufficient. Multiple leads with vectorcardiographic display are complementary and for optimal diagnosis by a computer electrocardiographic system may be preferred. Other systems of orthogonal leads or praecordial leads may be superior, but redundancy of information will always be important. For diagnostic sensitivity we prefer to combine the 15-lead system and vectorcardiogram with 'or-logic', and for specificity we prefer 'and-logic'. This study has shown that 'criteria for the diagnosis of infarction and also for the diagnosis of left ventricular hypertrophy or ischaemia are influenced by the presence or absence of other electrocardiographic abnormalities and appropriate weighting should be included in the programme. When clinical information is stored alongside the electrocardiogram, this information may also be used.

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## APPENDIX A

12-lead	Frank 3-lead	Diagnosis
<i>Hybrid logic for inferior infarction*</i>		
1) Q wave of $\geq 0.2$ mV and $\geq 30$ ms in II, III, and aVF	—	Inferior infarction
2) Q wave of $\geq 0.2$ mV and $\geq 30$ ms in any 2 leads of II, III, and aVF	Q in Y $\geq 0.1$ mV or Q/R ratio in Y $\geq 0.2$	Inferior infarction
3) Q wave of $\geq 0.2$ mV in any 2 leads of II, III, and aVF or Q wave of $\geq 0.1$ mV and $\geq 30$ ms in 2 leads of II, III, and aVF	Superior forces $\geq 30$ ms in frontal plane VCG	Possible inferior infarction
4) —	Q/R ratio in Y $\geq 0.25$ and Q wave $\geq 30$ ms duration	Possible inferior infarction
5) Q duration $\geq 0.1$ mV and $\geq 20$ ms in any 2 leads of II, III, and aVF (if QRS axis $> +60^\circ$ )	Q/R ratio in Y $\geq 0.2$ and Q wave $\geq 20$ ms duration	Possible inferior wall infarction
<i>Hybrid logic for anterior infarction*</i>		
12-lead	Frank 3-lead	Diagnosis
1) No R wave in V1 and V2 and V3, or V3 and V4, or V4 and V5	—	Anterior infarction
2) —	Absent Q in Z	Possible anterior infarction
3) R in V2 and V3 or V3 and V4, or V4 and V5 $\leq 0.1$ mV	Q/R ratio in Z $< 0.1^\dagger$ or 20 ms initial forces do not enter $+90^\circ$ to $-90^\circ$ in sagittal plane and $0^\circ$ to $+180^\circ$ m horizontal plane VCG	Possible anterior infarction
4) R in V2 and V3 $\leq 0.3$ mV	No anterior forces in horizontal and sagittal planes	Possible anterior wall infarction

\*'And-logic' requires the 12-lead criterion and either the orthogonal or vectorcardiographic criterion. 'Or-logic' requires either 12-lead criterion or an orthogonal criterion or a vectorcardiographic criterion.

$^\dagger$ Note Q/R ratio in Z only measured if R in Z  $> 0.5$  mV.

## APPENDIX B

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### *Definite myocardial infarction*

- 1) History of increasing angina pectoris and pain for  $\geq 2$  hours at rest  
plus
- 2) Serial AST, LDH, and CK elevation  
plus
- 3) Elevation of ESR or white blood count  
or
- 4) Coronary arteriographic evidence of occlusion and history of infarction or necropsy confirmation

### *Probable myocardial infarction*

- 1) History of increasing angina pectoris  
plus
- 2) Final diagnosis of recent or old myocardial infarction

### *Definite left ventricular hypertrophy*

- 1) Precipitating factor: at least one of the following:
  - a) Diastolic blood pressure  $> 90$  mmHg on 3 or more occasions
  - b) Diastolic blood pressure  $> 100$  mmHg on 2 occasions
  - c) Aortic valve disease or mitral regurgitation
  - d) History of hypertension in the past and 1 recording of  $> 90$  mmHg diastolic  
plus at least one of the following:
- 2)
  - a) Severe cardiomegaly clinically or radiographically
  - b) Confirmation of suspected lesion by cardiac catheterization  
or
- 3) Evidence of left ventricular hypertrophy or valvular lesion at surgery or necropsy

### *Probable left ventricular hypertrophy*

- 1) As above  
plus
- 2) Moderate cardiomegaly radiographically or clinically  
or
- 3) Past history of hypertension or known valvular lesion for at least 5 years

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*Abbreviations:* AST—serum aspartate aminotransferase. LDH—serum lactic acid dehydrogenase. CK—creatinine kinase.